THE GERB DE-SCAN MECHANISM – LUBRICANT SOLUTION DEVELOPMENT AND IN-ORBIT PERFORMANCE

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1. ABSTRACT

The GERB instruments fly on the MSG series of satellites and are designed to measure the Earth Radiation Budget (ERB). Several ERB satellites have been flown in low earth orbit, but this type of measurement has not been achieved before from geostationary orbit. It is expected that these measurements will make a major contribution to the understanding of our climate system and to the changes occurring in the average temperature of the Earth.

MSG is a spinning platform and this raised many challenges for the design and testing of the mechanisms, significantly a constant acceleration of 16g throughout the 7 year mission life for the GERB instrument.

MSG1 was launched in August 2002 and a significant amount of mechanism performance data is now becoming available.

This paper briefly describes the instrument and the two mechanisms, which form a crucial part of it, the Quartz-Filter and De-Scan Mechanisms. The lubrication requirements for the latter were extremely demanding, as the mission lifetime is equivalent to 200 million revs. A detailed discussion of the extensive bearing testing carried out in order to develop and demonstrate the suitability of the selected lubricant solution is presented, together with in-orbit mechanism performance data which covers the initial commissioning activities.

2. INTRODUCTION

The GERB instrument and mechanisms have been described in previous papers (Ref 1), so a very brief description is given here.

GERB is an Announcement of Opportunity instrument to be flown on a spinning MSG (Meteosat Second Generation) satellite in geostationary orbit. It measures the thermal infrared (IR) emitted from the Earth and the non-absorbed 'visible' sunlight (SW) reflected from Earth, uniquely providing 24 hours coverage. The principal design features of the instrument are summarised as follows:

- 3 mirror anastigmatic telescope
- Wide band linear detector array
- Rotating scan mechanism
- Channel separation via quartz filter
- Black Body for thermal calibration
- Solar diffuser for short wave calibration

The GERB instrument consists of two units plus the Inter-Unit Harness: the Instrument Optics Unit (IOU) and the Instrument Electronics Unit (IEU). The IOU measures 450mm x 200mm x 200mm and contains the imaging optics, detector system, DSM, QFM, on-board black body and the short wavelength calibration monitor. The IEU receives detector data, formats it and passes it on to the spacecraft data handling system. It also provides regulated power to all the subsystems, thermal control of the IOU, command and data interfaces and instrument health monitoring and control.

At the core of the GERB instrument is a broadband, three-mirror telescope housed in the Instrument Optical Unit (IOU). The configuration of the IOU is shown in Figures 1 and 2.

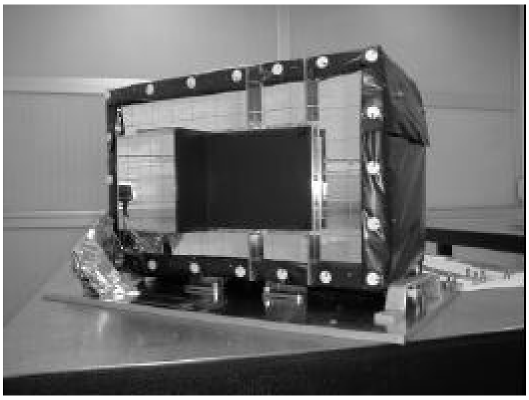

Figure 1. GERB IOU PFM

The IOU views the Earth with a black, wide-band, linear detector array, providing measurements of the Earth's output radiation in a total band 0.32µm - 30µm, and a short wave band 0.32µm - 4.0µm. A long wave band, 4.0µm - 30µm, is obtained by subtraction. A quartz filter placed in and out of the beam at the front of the telescope provides the switching between bands. In order for the detectors to obtain sufficient signal to meet the signal-to-noise requirement during each 15 minute MSG product, and to accommodate GERB on the spinning MSG platform, GERB provides a de-spin mirror to increase the length of available exposure per spin.

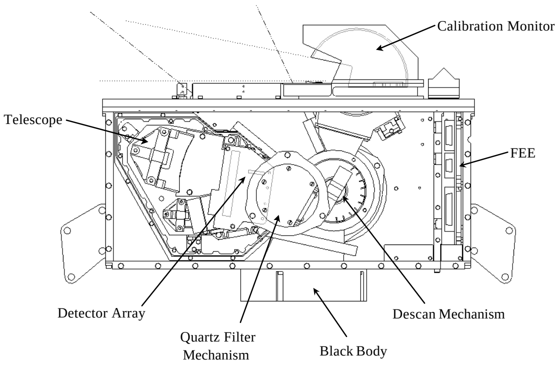

Figure 2. Plan view of GERB IOU

The face of the Earth visible from the MSG platform is viewed by a 1 x 256 pixel detector array via the despin mirror, the 3 - mirror anastigmatic telescope and an anti-polarisation fold mirror. The telescope is designed to enable the detector array to view the full 18° north-south field of view of the Earth. Full coverage of the Earth is achieved by adjusting the phase of the despin mirror so that each image consists of a series of consecutive strips in the north-south direction.

The same telescope and detector are used to make measurements in the two spectral bands. The required longwave measurement is obtained by subtraction during ground processing. This dual use of telescope and detector implies physical co-registration between bands but individual measurements cannot be made temporally coincident. Two complete spectral images of Earth are produced every 300 seconds. This data is averaged together to produce a fifteen minute image during ground processing.

The telescope views the Earth or calibration sources from the DSM, which scans past the aperture of the optics unit, in the direction, counter to the spacecraft spin and at half the spacecraft rate. This motion effectively produces a shuttered frozen Earth view for a fraction of the satellite rotation period 600ms.

Direct sunlight will damage the detector and so protection mechanisms are incorporated into the GERB design.

3. QFM DESIGN IMPLEMENTATION

The Quartz Filter Mechanism (Figure 3) is a compact, insertion mechanism which performs the switch between total and short wavelength measurement This is implemented by rotating a filter holding turn-table through the optical path between the de-spinning mirror and the telescope.

The shutter function is also incorporated to avoid direct sun radiation into the detector which would cause catastrophic failure of some pixels. Sun illumination can occur during early orbit phases, when GERB is not powered and not synchronised to the MSG spin, and near eclipse conditions.

Figure 3. Quartz Filter Mechanism

4. DSM DESIGN IMPLEMENTATION

The De-Scan mirror Mechanism, DSM, shown in Figure 4, is a plane double sided mirror mechanism counter-spinning at 50 rpm in the opposite sense of the 100 rpm spinning spacecraft. During its scan, it reflects the incoming light beam into the instrument telescope and, hence, generates one 40 msec stationary image of the Earth for each revolution of the spacecraft.

Figure 4. De-Scan Mirror Mechanism

The mirror must also rotate to allow a calibration sequence to be performed by viewing a black body and a solar calibrator at defined intervals within the scan cycle.

The rotating components of the DSM (Figure 5) consist of three main parts; the plane double-sided mirror, the torque motor rotor and the rotor of the rotary Inductosyn ® position transducer. These are mounted on a titanium alloy shaft.

Figure 5. DSM Rotating Equipment

The aluminium alloy mirror is 18mm thick, 56 mm high, 76 mm wide, which contributes to positioning the CoG of the rotating equipment equally between the supports of the shaft. The flatness is 0.1 fringes and micro roughness better than 2 nm_{RMS}. The mirror faces are finished with an enhanced reflective silver-based coating.

Below the mirror a wide titanium flange acts as a labyrinth cover against wear debris, a balancing flange and also a moving axial stop.

On the opposite end are shown the motor rotor, the lower balancing flange, and the rotary transducer rotor.

A pair of angular contact bearings with 47 mm outer diameter and high conformity races (1.08) are mounted between the ends of the shaft and softly preloaded.

To match the bearing seats the aluminium alloy housing is lined with hardened stainless steel to avoid CTE mismatching.

Motion accuracy requirements were another key requirement which had a strong impact on the tolerarances of the mechanical design:

- Linearity 650 µrad
- Repeatability 28 µrad over 15 mins
- Wobble 650 µrad
- Wobble repeatability 28 µrad
- Jitter 65 µrad

Measurements of the above requirements have exceeded specification. This margin includes wobble even though the sliding bearing bore had to be increased by 10 µm, in comparison to the manufacturer's guidelines, to ensure the correct pre-load performance.

As for QFM, the dynamic balance of the rotating part of the mechanism was required to be better than 0.2 gmcm, to reduce disturbances of the instrument to a minimum. An even lower value was easily achieved by the means of a fine dynamic balancing set-up.

No launch locking was provided for the bearings. The only mechanical protection are three pin stops fitted in the housing. These impinge on the upper balancing flange during launch to prevent impacts between the separate Inductosyn ® parts, and assure a 0.1 mm gap.

4.1 Motor and encoder selection

Several designs were considered for the DSM motor. A brushless torque motor produced by ETEL was selected as offering the best combination of drive torque, low detent torque and geometry.

Mechanisms of this type have traditionally used optical encoders for position control. These have several drawbacks, including fragility, very precise alignment and can possible fail due to the ingress of bearing debris obscuring the optical sensor. Predicting that the GERB mechanism was likely to develop significant amount of debris an inductosyn encoder, produced by Farrand, was selected. These devices are rugged, high resolution and are not susceptible to debris contamination.

4.2 Motor drive electronics

The control electronics are designed to synchronise the position and phase of the mirror with respect to the spacecraft generated start of line pulse. The mirror should track a single pixel as the spacecraft rotates with minimum jitter and smear and each rotation increment the phase to image the next line on subsequent rotations.

It was designed to accommodate a large range of operating conditions of the mechanism, particularly because of the unknown condition of the bearings at end of life.. In order to allow some safety margin the torque available to drive the motor can be set to one of 8 levels.

The inductosyn position transducer is continuously monitored and compared with where the mechanism should be, on board. This is the position error, and is used to measure the performance of he system as a whole and is a good indication of the bearing noise.

5. LUBRICATION SELECTION AND INITIAL TESTING

From the start of the mechanism design process, life under a constant radial acceleration of 16 g was understood to be the most demanding and most critical requirement for the mechanism and, in particular, for its bearings. No proven solution existed for such an operating environment.

Due to the proximity of optical surfaces solid lubrication was the preferred option. The baseline lubrication system was ion plated lead, as widely used for many years in European space applications. In 1g, the classic combination of leaded-bronze cage with ion-plated lead on raceways has performed > 10^9 revs in vacuum and so would be expected to provide a promising candidate for the GERB application. In addition to separating the balls, the leaded-bronze cage performs the essential lead re-supply function of transferring free lead from the lead-bronze matrix via balls to raceways. However a conventional cage design could not be considered for GERB because its high mass would have generated quite large volumes of wear debris under 16g and so potentially considerable bearing torque noise and possible premature failure. Hence the initial belief that selection of the lubricant system and minimisation of the cage wear debris generated would be a major challenge for GERB..

Due to the unusual friction and wear issues the necessity to test in vacuum on a purpose built centrifuge (Fig. 6) to simulate the spacecraft environment was deemed mandatory.

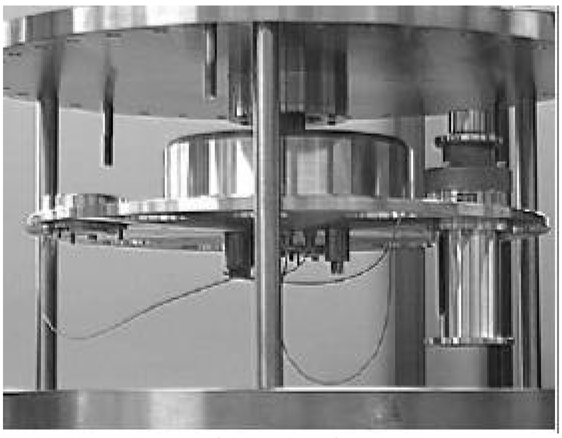

Figure 6. Lifetest Centrifuge at ESTL

Prior to comissioning of the centrifuge an initial 1g lubricant screening programme was carried out in which a number of candidate lubricant systems were evaluated in-vacuum.. From this initial screening test programme, the most promising three candidate solutions, namely ion-plated lead with a hybrid polymeric cage featuring lead-bronze inserts in a Vespel SP3 cage structure, shown in Figure 7 below, and MoS_2 coated steel balls and raceways with Vespel SP3 spacer balls, and leaded bronze balls alternating with steel balls (ion-plated lead raceways) were tested in the centrifuge facility at ESTL.

Figure 7. DSM Hybrid Cage

The hybrid cage solution proved the most successful of the 3 candidates tested and offered the combination of lead-replenishment via its inserts and low mass due to the Vespel structure. This configuration out-performed and out-lived the two other options during testing on the centrifuge, however the test prematurely stopped after the equivalent of 2.5 years operation.

On inspection following cessation of the test it was found that the generation of debris was somewhat higher (732mg total wear mass compared to prediction of 160mg) and much more concentrated across a small arc of the bearing seat than was expected. Insufficient debris capture volumes surrounding the bearings caused the wear debris to choke and jam the bearings, resulting in a premature stoppage of the DSM life test.

Despite the choking of the bearings by debris, further examination indicated that the lubricant and bearing elements were still in good tribological condition.

On the basis of the measured wear of the most worn cage after 2.5 year equivalent life, a volume of 245 mm^3 along and arc of 30° was extrapolated to be needed to accommodate the cage debris generated over the equivalent of 7 years life in the MSG spacecraft environment. However it proved possible to incorporate capture volume traps, aligned with the direction of the centripetal acceleration , of 1700 mm^3, i.e. ~7 times greater than the required extrapolated volume.

These larger capture volumes were incorporated into the design of the flight units and the life-test models (LTMs) to be used in the next phase of bearing life-testing.

6. SUBSEQUENT BEARING TESTS

The first attempt at life-testing the LTMs with the enlarged debris capture volumes was also prematurely halted, in this case due to a non-flight-representative bearing ring misalignment in the LTM units which resulted in gross cage wear after less than 30 million revs in vacuum.

Following this further set-back, the test philosophy was reviewed in detail and a number of previous assumptions and decisions re-visited, with the intention of achieving a more flight-representative test setup and methodology.

In order to try to improve understanding of the cage wear phenomena, two off-line tests were carried out in 1g with the rotational axis of the bearings horizontal (Test Phases “3a” and “3b”). In the first such test the bearings were heavily preloaded to 160N with the peak Hertzian ball-raceway contact stress around 1150MPa. This test was representative of the peak ball-raceway stresses experienced by the most heavily loaded ball in the flight bearings, 980MPa, plus margin though in other respects the test setup matched the flight and life-test configurations. In the second test, the preload was 50N, resulting in a peak stress around 800MPa , closer to the lower limit of stress in the bearings in-flight (704MPa).

These Phase 3 tests revealed that, firstly the cage wear rate after 10 million revs in-vacuo in each case was much higher than the 2mg predicted by the equilibrium wear equations (See Table 1) . The most likely reason for this is that the high wear rates associated with running-in effects were a dominant part of the wear process even after 10 million revs in-vacuo. Secondly the wear rate in the less highly stressed bearing pair was lower than in the high-stress Phase 3a bearings. This suggested that ball-raceway contact stress has a large effect on cage wear rate (something reported elsewhere in polymeric bearings (see Ref. 2).

	Peak Hertzian Stress (MPa)	Total Cage Wear (mg)
Phase 3a	1150	117
Phase 3b	800	36

Table 1. Cage Wear Masses after 10 million Revs 1g Horizontal Axis In Vacuum

It was also noted during the Phase 3a test that after each periodic bearing directional change (torque reversals – needed to identify the bearing mean torque) large torque spikes were generated. Torque spikes were correlated visually with the cage becoming lodged into a “non-preferred location” within the bearing such that there is some increasing element of cage drag and probably larger cage/ball or cage/land forces.

Finally the classic impact of environment on bearing performance was once again demonstrated, for example upon venting the test chamber after Phase 3a, there were increases in mean torque from 150 to 200gcm, and in zero-peak torque from 220 to almost 600gcm after performing only 4 further revs in air. This type of characteristic is typical of bearings which have significant lead-bronze transfer to balls and raceways when operated in air and is due to the different in-air and in-vacuo friction and wear properties of lead-bronze (and in this case of Vespel SP3 too).

The Phase 3 testing led to changes in the test setup and methodology used for the life-testing on the centrifuge, particularly in the following areas:

- Motion profile
- Bearing loading

Motion Profile

In-flight the unit operates constantly at 50rpm, however earlier life-tests had been accelerated with operation mainly at 500rpm, hourly decelerations to 50rpm and periods of oscillatory motion to enable characterisation of the mean torque of the test bearings, then re-acceleration to 500rpm. Based on the Phase 3a results it seemed that this practice not only increased the bearing torque noise but may also have increased the cage wear rate by forcing increased cage /ball interactions.

It was therefore agreed that the life-test should be run as far as possible in uni-directional motion at 500rpm. To facilitate this, the facility was modified to monitor bearing mean torque deduced from the drive motor current, rather than from a Kistler torque transducer as previously.

Bearing Loading

The Phase 3 tests had demonstrated the influence of bearing ball-raceway contact stress on cage wear rate, and therefore emphasised the need to match in-flight and in-test ball-raceway contact stresses as closely as possible in the life-test.

Due to this requirement a change was made to the centrifuge facility test setup. The overhung motor design, in which, the life-test model (LTM) was rigidly coupled to a motor shaft which supported the motor rotor and resolver with a single support bearing at the lower end of the drive motor was rejected. In its place, an upgraded test setup was used in which the motor rotor assembly was supported on its own spring preloaded bearing pair, and the motor shaft was coupled to the LTM shaft using an “Oldham” coupling. By reducing to negligible levels the axial and radial forces and moments which could be transmitted from motor to LTM drive shaft, the impact of the motor on the LTM bearing performance was also minimised.

With these modifications, a third and final centrifuge life-test was commenced, with 3 LTM test stations used. LTM’s 1 & 3 were lubricated by ion-plated lead with the hybrid Vespel SP3 cage described earlier, however the backup LTM2 solution featured the addition of a small quantity (~20mg) of Braycote 601EF micronic grease to each bearing. To minimise egress, labyrinth seals were designed and fitted and creep barriers applied whilst maintaining similarity of LTM housing and bearing loads with any potential future grease-lubricated flight model. Prior to test the LTM’s were subjected to simulated launch vibration testing.

In order to simulate the ground-testing of the instrument, the first part of the life-test was carried out in air at 50rpm for 36000 revs with rotational axis vertical. It should be noted that this speed is rather high for in-air operation of ion-plated lead lubricated bearings, for which more typical practice is to constrain operation to <20-30rpm and for $<10^5$ revs. No such restrictions apply in vacuum. During testing, the bearings became increasingly “noisy”, with mean torque increasing by around 50% to roughly 120gcm and peak torque increasing markedly from around 100-150gcm to of order 1000-1600gcm. Though both LTMs exhibited similar behaviour, the performance of LTM1 was marginally better than that of LTM3.

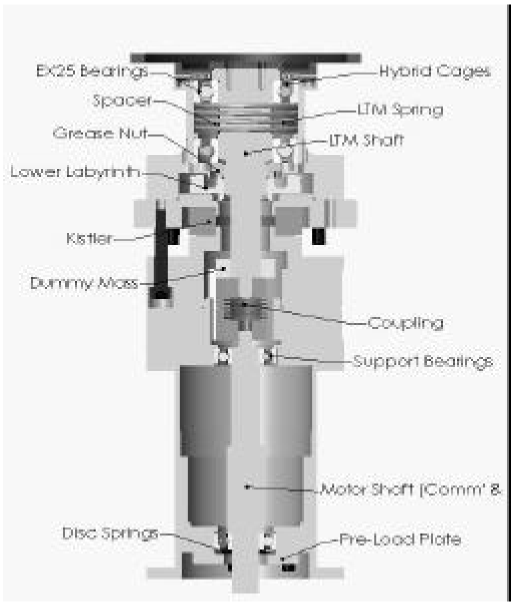

Figure 8: Upgraded LTM Drive Motor and Housing

Due to concerns that this torque noise and the accompanying acoustic noise could indicate some potentially major bearing issue, each LTM was paused twice during the ground-test and subjected to a minimally intrusive inspection (in-situ without modification of bearing preload). There was some evidence of lead-bronze transfer during these inspections and clearly the high friction and wear rate of lead-bronze (and Vespel SP3) in air may have contributed to the noisy torque performance, however the visual condition was not concerning, therefore the test was continued.

Following the in-air testing, the bearings were then operated in-vacuo for 960000revs prior to operation of the centrifuge. During this phase it was notable that typically low mean and peak torque behaviour returned rapidly, within around 100000-300000revs (equivalent to a few days in-flight operation) for both LTMs 1 & 3.

Finally the life-test itself was commenced with the bearings operating on the centrifuge which subjected them to radial acceleration of 16g for the entire 404 day duration of the test. During this time, the bearing torque performance was monitored continuously.

Testing of LTM1 was suspended after 138.1million revs, a little more than one original flight lifetime (3.5 years requirement) with margin in order to preserve evidence of its condition in the event of an unacceptably high cage wear rate being discovered in LTM3.

Operation of LTM3 was terminated after successful completion of 230million revs. Over this period the mean torque was typically in the range 50-100gcm, with peak torque usually around 125-175gcm.

LTM2 was operated at 111rpm, a speed selected to provide similarity of operational base-oil film thickness conditions in-flight at 50rpm and ~10°C and in the accelerated test at approximately 40°C. Due to the suspension of testing on completion of the required duration for LTM3, operation of LTM2 was suspended after 75.3million revs.

Both LTMs 1 & 3 were found to have some degree of cage-pocket wear as typified in Figure 9 which was however much lower than in earlier centrifuge life-tests. In addition there was a considerable amount of lead-bronze transfer, with balls and raceways showing evidence of some transfer.

Figure 9 LTM3 lower cage pocket showing wear marks

LTM2 had no significant cage wear and the cage pockets were found to be in excellent condition with the original machining marks still present.

Post-test examination showed that the spring preload systems of all three LTM units were functioning normally and the preload remained correctly set in each case. The cage mass losses, which were broadly in-line with predictions were as shown in Table 2 below.

	Millions of Revs Completed Under 16g radial Acceleration.	Total Wear Mass of Cages (mg)
LTM1	138	291
LTM2	75	19
LTM3	230	243
Predicted	230	194-512 (μ=0.05-0.15)

Table 2. Cage Total Mass Loss Summary

7. CONTAMINATION STUDIES

In the initial phases of life testing the results were not encouraging and the likelihood of identifying a suitable dry lubrication system began to look bleak. At this point it was decided to adopt a grease-lubricated system as a backup.

Grease would provide adequate lubrication, but the issue of contamination in an optical instrument is always a problem. GERB is designed to make very accurate radiometric measurements so the performance of the optical surfaces is critical.

To allow a quantitative decision to be made a test programme was set up to establish the effects of contamination of Braycote 601. It was known from manufacturers data and previous tests that this grease has a very low vapour pressure and tests at RAL confirmed that it is very difficult to deposit this material under vacuum on a room temperature surface. However, in the case of GERB, the scan mirror runs cold, about 0°C, and is illuminated by the sun as the satellite and the mechanism rotate.

A test rig was set up to mimic these conditions with a heated sample of Braycote, a cold witness sample and solar spectrum illumination. The rig was maintained under these conditions for several days and then the sample removed and the optical performance measured in an infrared spectrometer. Even after this very short test significant degradation of the sample's optical performance was identified.

These results showed that even though the grease does probably give better lubricating performance, the risk of contamination to the optics is very real. If any grease or outgassing products from the grease reach the mirror, the performance will degrade rapidly.

Consequently the baseline design for all GERB instruments is the dry system described in this paper. However, the opportunity still exists to change to grease on later models if in orbit data shows this to be advantageous.

8. IN-ORBIT PERFORMANCE

MSG1 was launched in August 2002 and GERB commissioning started in December with the first images being produced on 12th December

The commissioning of the despin mechanism started with running the mechanism at various torque levels (see section 3.2) to establish the best running level. If it is set too low the mechanism may loose lock and if set too high then the jitter increases.

The mechanism failed to remain reliably in lock below level 4 and so was left at this level for a few days while the mirror position error telemetry was being monitored. The position error continued to reduce over the next few days and so the torque level was reduced to 3, which has become the normal running level. Position errors remain low indicating good running of the mechanism and its bearings. Overall performance of the system is good with position errors within specification.

Close inspection of the position and velocity error signals, sent to the ground in the housekeeping telemetry from the instrument, show a similar behaviour to that measured during the life test. Different parameters are being measured but behaviour with periods of smooth running and periods of less smooth running are evidence. This gives confidence that the life tests were a valid qualification for this mechanism.

Initial indications of the errors in the instrument performance introduced by the mechanism are:

Jitter (east-west effect) 0.03% SW 0.1% LW

Smear (north- south effect) 0.02% SW 0.08% LW

This is well within the required specification. Figure 10 shows the first image from GERB.

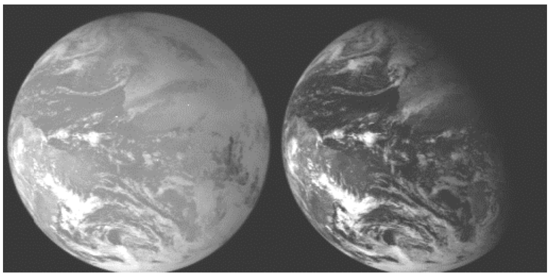

Figure 10. The first image from GERB, left is the total channel and right is the short-wave channel

9. LESSONS LEARNED AND CONCLUSIONS

Like many dedicated instrument developments, the GERB development has been a lengthy one, reflecting the complexity of the instrument and the technical challenges addressed during the programme. Ultimately however, as demonstrated by the successful early in-orbit data, the instrument performance is well within the required specification.

The GERB bearing test programme was one of ESTL's longest and most complex test programmes dedicated to a single instrument application, reflecting the scale of the tribological challenges of the application. However the main conclusion is that it has ultimately been demonstrated that the selected lubricant system is capable of performing the required in-orbit duty with usual ECSS margins applied.

ESTL's early involvement in the programme enabled a full range of lubricant candidates to be screened and a rigorous down-selection and on-centrifuge test campaign to be carried out. Nevertheless, a number of test-related lessons have been learned, namely:

1) the importance of accurate assessment of in-flight loads and velocity profiles and the close simulation of these by appropriate test facilities and methods.

2) the need for adequate provision for wear debris management

3) the need to include provision for accurate control and confirmation of bearing alignment in both flight and test units. – where possible by direct measurement

When these issues were addressed in the final life-test, the cage wear rates obtained were much lower and the torque performance much better than in previous test phases.

It is also interesting to note the high torque noise caused when running lead-bronze caged, ion-plated lead lubricated bearings outside ESTL's normal guidelines for this lubricant in air (at speeds >20rpm and for durations >10^5 revs). Still more interesting is the rapid pace of apparent recovery of the bearings once introduced into vacuum operation (apparently observed both in test and in-flight). There was no evidence that the in-air operational regime required for GERB reduced the lifetime of the lubricant system.

Finally it may be useful in future programmes to recall that test "failures" can alternatively be viewed as avoidance of in-orbit anomalies. If this maxim is true then we can expect GERB to deliver a long and trouble-free in-orbit lifetime.

10. REFERENCES

1 "GERB rotating mechanisms for MSG", D.Smart D., Sawyer E., Fabbrizzi F., Campioni V., Proceedings 8th ESMATS (ESA-SP-438).

2 "Parametric Study of Solid-Lubricant Composites as Ball-Bearing Cages" Stevens K.T & Todd. M.J. "Tribology International October 1982

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